



Giant planet formation via pebble accretion

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Resumen / En el marco del modelo clásico de acreción del núcleo, la formación de un planeta gigante ocurre por dos procesos principales: primero se forma un núcleo masivo por acreción de sólidos presentes en el disco protoplanetario; luego, cuando el núcleo excede un valor crítico (generalmente mayor a $10 M_{\oplus}$) se dispara la acreción del gas circundante y el planeta acreta grandes cantidades de gas en un período corto de tiempo (del orden de 10^5 años) hasta que el mismo alcanza su masa final. De esta manera, la formación de un núcleo masivo tiene que ocurrir cuando aún hay gas disponible para ser acretado en el disco. Esto impone una fuerte restricción temporal en la formación de los planetas gigantes, dado que prácticamente no se observan discos protoplanetarios en estrellas con más de 10^7 años. La formación de núcleos masivos en un tiempo menor a 10^7 años por la acreción de planetesimales grandes (con radios > 10 km) solo es posible a partir de discos protoplanetarios masivos. Sin embargo, las tasas de acreción aumentan significativamente para planetesimales de menor tamaño, especialmente para las *pebbles*: partículas con tamaños del orden del mm y cm, las cuales están, desde un punto de vista dinámico, acopladas fuertemente al gas. En este trabajo, analizaremos la formación de planetas gigantes incorporando las tasas de acreción de *pebbles* en nuestro modelo global de formación planetaria.

Abstract / In the standard model of core accretion, the formation of giant planets occurs by two main processes: first, a massive core is formed by the accretion of solid material; then, when this core exceeds a critical value (typically greater than $10 M_{\oplus}$) a gaseous runaway growth is triggered and the planet accretes big quantities of gas in a short period of time until the planet achieves its final mass. Thus, the formation of a massive core has to occur when the nebular gas is still available in the disk. This phenomenon imposes a strong time-scale constraint in giant planet formation due to the fact that the lifetimes of the observed protoplanetary disks are in general lower than 10 Myr. The formation of massive cores before 10 Myr by accretion of big planetesimals (with radii > 10 km) in the oligarchic growth regime is only possible in massive disks. However, planetesimal accretion rates significantly increase for small bodies, especially for pebbles, particles of sizes between mm and cm, which are strongly coupled with the gas. In this work, we study the formation of giant planets incorporating pebble accretion rates in our global model of planet formation.

Keywords / Planets and satellites: gaseous planets – Planets and satellites: formation

1. Introduction

In the standard core accretion model the main question regarding giant planet formation is how to form massive cores before the dissipation of the protoplanetary disk. Ormel & Klahr (2010) and Lambrechts & Johansen (2012) demonstrated that small particles, often called *pebbles*, with Stoke number $S_t \lesssim 1$ are strong coupled to the gas and are very efficiently accreted by the planets. The main difference with planetesimal accretion is that pebbles can be accreted by the full Hill sphere of the planet while planetesimals can only be accreted by a fraction of the Hill sphere, $\alpha^{1/2} R_H$, with $\alpha = \sqrt{R_c/R_H}$, being R_c the core radius of the planet and R_H the Hill radius of the planet. The formation of massive cores before 10 Myr by accretion of big planetesimals (with radii > 10 km) in the oligarchic growth regime is only possible in massive disks (Fortier et al., 2013; Guilera et al., 2014). Thus, pebble accretion appears as a new alternative in the formation of giant planets (Lambrechts et al., 2014). In this work, we study the formation of a massive cores incorporating the pebble

accretion rates in our model planet formation (Guilera et al., 2010, 2014).

2. Our model of planet formation

In a series of previous works (Guilera et al., 2010, 2011, 2014). we developed a model which calculates the simultaneous formation of planets immersed in a protoplanetary disk that evolves in time. In this new work, we incorporate some improvements to our previous model, especially the pebble accretion rates given by Lambrechts et al. (2014) in order to study the formation of giant planets by pebble accretion. The main characteristics of our model are,

Planets:

- solid cores grow by planetesimal accretion (in the oligarchic regime) or by pebble accretion,
- gas accretion and the thermodynamic state of the planet envelope are calculated solving the standard equations of stellar evolution.

The protoplanetary disk:

- the gaseous component evolves as an α accretion disk with photoevaporation,
- the planetesimal or pebble population evolves by 3 factors: accretion by the planets, migration due to gas drag (3 regimes: Epstein, Stokes and quadratic), and collisional evolution

2.1. Evolution of the disk

As we mentioned above, the gas surface density of the disk Σ_g evolves as an α accretion disk (Pringle, 1981) with photoevaporation (Dullemond et al., 2007)

$$\frac{\partial \Sigma_g}{\partial t} = \frac{3}{R} \frac{\partial}{\partial R} \left[R^{1/2} \frac{\partial}{\partial R} \left(\nu \Sigma_g R^{1/2} \right) \right] + \dot{\Sigma}_w(R), \quad (1)$$

where R is the radial coordinate, ν is the viscosity, and $\dot{\Sigma}_w$ represents the sink term due to photoevaporation.

Regarding the solid component of the disk, this obeys a continuity equation for the solid surface density Σ_p

$$\frac{\partial \Sigma_p}{\partial t} - \frac{1}{R} \frac{\partial}{\partial R} \left(R v_{\text{mig}}(R) \Sigma_p \right) = \mathcal{F}(R), \quad (2)$$

where v_{mig} is the planetesimal or pebble migration velocity and \mathcal{F} represents the sink terms due to the accretion by the embryos (Guilera et al., 2010).

2.2. Growth of the planets

We considered that the cores of the planets grow by planetesimal and pebble accretion. For planetesimals, we use the planetesimal accretion rates given by Inaba et al. (2001), while for pebbles we use the pebble accretion rates given by Lambrechts et al. (2014). So, the solid accretion rates in our model are given by

$$\frac{dM_c}{dt} = \begin{cases} \left. \frac{dM_c}{dt} \right|_{\text{planetesimal}}^{\text{Inaba}} & \text{if } S_t \geq 1, \\ \left. \frac{dM_c}{dt} \right|_{\text{pebble}}^{\text{L\&J}} & \text{if } S_t < 1, \end{cases} \quad (3)$$

with

$$\left. \frac{dM_c}{dt} \right|_{\text{planetesimal}}^{\text{Inaba}} = 2R_H^2 \Sigma_p \Omega_P P_{\text{coll}}, \quad \text{if } S_t \geq 1, \quad (4)$$

$$\left. \frac{dM_c}{dt} \right|_{\text{pebble}}^{\text{L\&J}} = \begin{cases} \beta 2R_H^2 \Sigma_p \Omega_P, & \text{if } 0.1 \leq S_t < 1, \\ \beta 2 \left(\frac{S_t}{0.1} \right)^{2/3} R_H^2 \Sigma_p \Omega_P, & \text{if } S_t < 0.1. \end{cases} \quad (5)$$

P_{coll} is a probability collision (see Guilera et al., 2010, for a detail explanation), and Ω_P is the keplerian frequency at the location of the planet. We introduced a factor β in the pebble accretion rates. This factor is defined as $\beta = \min(1, R_H/H_p)$, and take into account a reduction in the pebble accretion rates if the scale height

of small pebbles, H_p , could be greater than the Hill radius of the planet. The scale height of the solids is given by (Youdin & Lithwick, 2007)

$$H_p = H_g \sqrt{\frac{\alpha}{S_t}}, \quad (6)$$

where H_g is the gas disk scale height, and α is the turbulence parameter of the gas disk assuming the Shakura & Sunyaev (1973) prescription.

Finally, the gas accretion rate and the thermodynamic state of the planet envelope are calculated solving the standard equations of transport and structure, using an adapted Henyey type code (Fortier et al., 2009; Guilera et al., 2010).

3. In situ giant planet formation at 5 au

We assumed that the mass of the central star and the mass of the disk are $M_\star = 1 M_\odot$ and $M_d = 0.05 M_\odot$. The initial gas and solid surface densities are given by

$$\Sigma_g = \Sigma_g^0 \left(\frac{R}{R_c} \right)^{-\gamma} e^{-(R/R_c)^{2-\gamma}}, \quad (7)$$

$$\Sigma_p = \eta \Sigma_p^0 \left(\frac{R}{R_c} \right)^{-\gamma} e^{-(R/R_c)^{2-\gamma}}, \quad (8)$$

with $R_c = 20$ au and $\gamma = 0.9$ (Andrews et al., 2010). $\eta = 0.25$, if $R < 2.7$ au, or $\eta = 1$, if $R \geq 2.7$ au. The disk is extended between 0.1 au and 1000 au using 5000 radial bins logarithmically equally spaced.

Before we calculated the in situ formation of the planet at 5 au, we first analyzed the evolution of the disk without any planet in it. For simplicity, we considered an unique size for the planetesimals/pebbles along the disk, and we did not consider the collisional evolution of them. So, the solid component of the disk evolves only by planetesimal/pebble migration. Fig 1 shows that the radial drift of small planetesimals and pebbles could play an important role in the formation of massive cores. While the inward migration of material significantly increases the surface density at 5 au, for some sizes (between 1 cm and 10 m) there is a quickly subsequent decline of such surface density. Thus, the planet has to be able to accrete the material before all of it moves inward.

Fig. 2 shows the growth of the planet core as function of time. Simulations stopped when the planet achieved the critical mass (when the envelope mass equaled the core mass) or when the disk was dissipated (at ~ 5 Myr). For pebble ($r_p \lesssim 1$ m) and small planetesimals ($1 \text{ m} < r_p < 100 \text{ m}$) the planet achieved the critical mass very quickly. However, in general the critical core masses are very large. But, Lambrechts et al. (2014) showed that when the planet become massive enough ($M_{\text{core}} \gtrsim 20 M_\oplus$), it can perturb the surrounding gas and halts the pebble accretion.

Finally, we calculated again the in situ formation of a planet at 5 au, but now considering a planetesimal size distribution. We used 46 size bins between 0.01 cm and 100 km logarithmically equally spaced. Initially, all

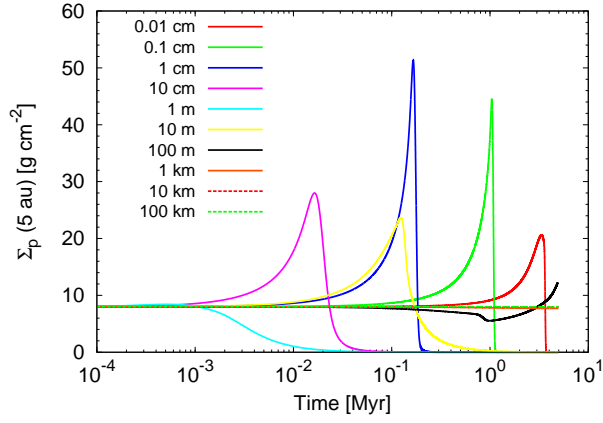


Fig. 1: Time evolution of the solid surface density at 5 au. The inward migration of small particles, from the outer region of the disk, significantly increases the surface density. For big planetesimals, the surface density remains almost constant until the dissipation of the disk.

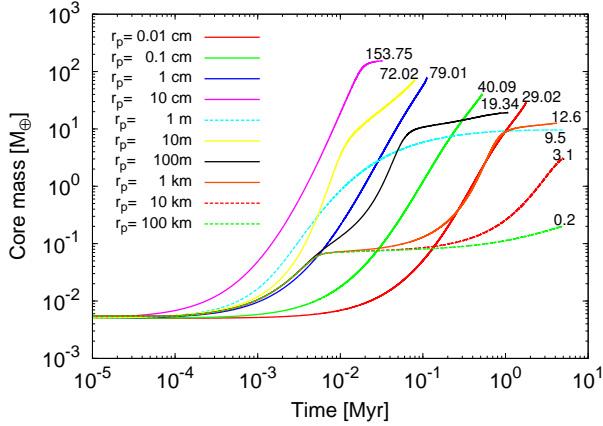


Fig. 2: Time evolution of the core mass of the planet. Pebbles ($r_p < 1$ m) are very efficiently accreted and massive cores are formed very quickly. Planetesimals with $1 \text{ m} < r_p < 100 \text{ m}$ are efficiently accreted too, due to the presence of the planet envelope which significantly increases the capture radius of the planet (Guilera et al., 2014). Solid lines represent the cases when the planet achieved the critical mass, and green lines the cases when not.

the solid mass is in the pebbles of 0.01 cm. The collisional evolution of the system is calculated using the model developed in Guilera et al. (2014) (considering coagulation/fragmentation between the particles along the disk). Fig. 3 shows the time evolution of the planet core mass. We can see the incorporation of the collisional evolution of the population of solids allow to the planet reached a massive core of about $10 M_\oplus$ in only ~ 0.2 Myr.

4. Conclusions

Pebble accretion appears as an interesting phenomenon in the formation of giant planets. The high accretion efficiency of these particles could solve the problem of the formation of massive cores before the dissipation of the protoplanetary disk. However, we consider that accu-

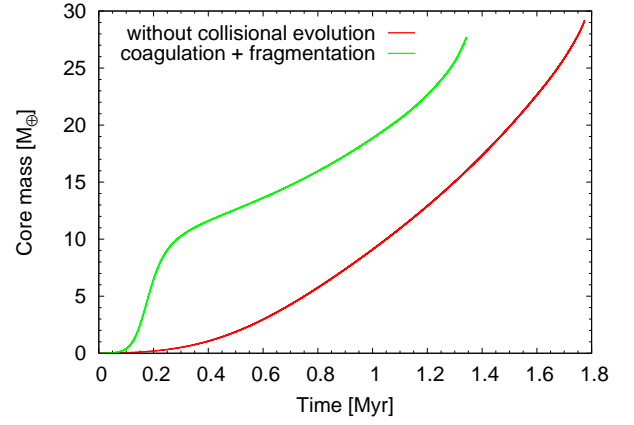


Fig. 3: Comparison of the time evolution of the planet core mass between the cases with, and without ($r_p = 0.01$ cm) solid collisional evolution. The coagulation between small pebbles significantly favors the quickly formation of a massive core.

rate models of collisional evolution, couple with models of planet formation, are needed due to the fact of the strong dependence between the time-scale of the solid accretion, solid migration, and the sizes of the bodies. Other important question, not treated in this work, is if these pebbles can always reached the core. When the mass of the core is a few times the mass of the Earth, the planet is able to bind a non negligible envelope and pebbles could be destroyed before reached the core. This situation could change the evolution of the growth of the planet, especially the accretion of gas (see Venturini et al., 2015).

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